RF and microwave mixers—a tutorial

By Roland K. Soohoo

Mixers are an essential and fundamental part of high-frequency communication systems. This tutorial describes a mixer's function, its theory of operation, semiconductors used, types of mixers and key specifications. This article is meant as an introduction for individuals who want a general understanding of mixer principles and operation.

A mixer is a component that acts as a frequency converter by "mixing" two input signals together to produce a desired output signal. Figure 1 shows the receiver portion of a typical RF communications system.

An RF signal is received at the antenna and typically is amplified by an RF amplifier because the amplitude of the input signal is usually small. The amplified signal is applied to one of the input ports of a mixer, and a second local oscillator signal is applied to the other input port. What emerges from the output port is a sum or difference of the input frequencies and other frequency components.

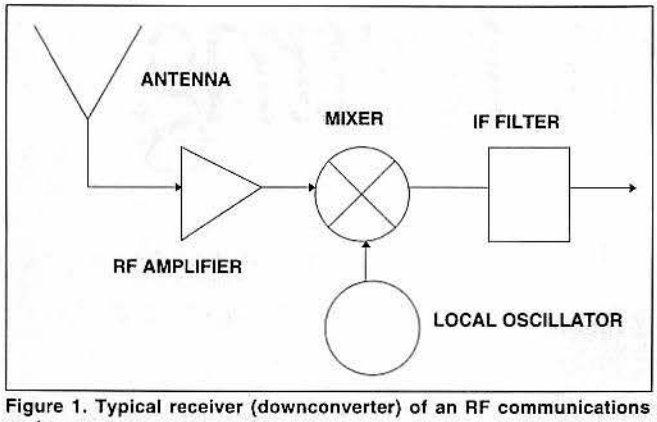


Figure 1. Typical receiver (downconverter) of an RF communications system.

Typically, in a receiver it is the difference frequency that is the desired signal. A filter is used at the output of the mixer to remove the undesired signals and to pass the desired signal to the rest of the communication system. As an example, if an 850 MHz signal were received by the antenna and an LO (local oscillator) signal of 800 MHz were applied to the mixer, a signal at 50 MHz would emerge from the output port, which is much lower in frequency than the original signal received at the antenna.

This type of RF receiver also is known as a downconverter because it converts a higher-frequency signal to a lower one. The signal is downconverted to enable the signal to be processed at frequencies that are easy to work with. The sum frequency at the output typically is used in a transmitter. Because the RF input frequency is converted into a higher frequency, this is known as upconversion. Matching and filtering networks are used to enhance either the sum or difference frequencies, depending on the application. The mixer is fundamentally a frequency conversion device that uses the non-linear and switching properties of semiconductor devices to achieve the mixing action.

Operation theory

A mixer can use a wide variety of semiconductor devices, such as bipolar junction transistors (BJTs) and field-effect transistors (FETs), nevertheless, diodes are one of the most popular. The simplest mixer uses a single diode, but some mixers use as many as 12. A typical single-diode mixer (also known as single-ended) is shown in Figure 2.

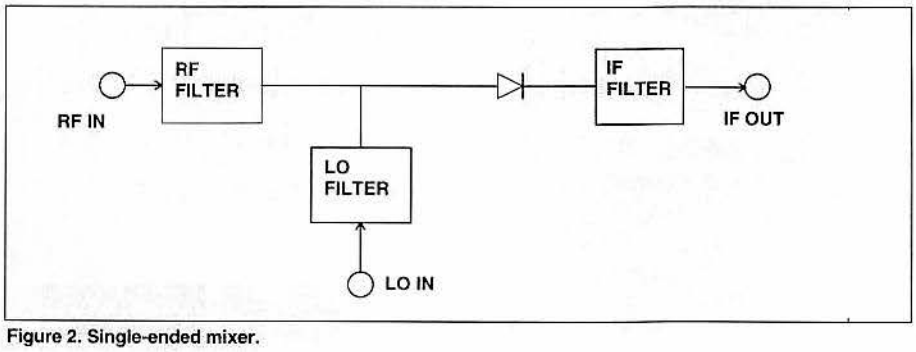


Figure 2. Single-ended mixer.

The three ports of the mixer include the radio frequency (RF), local oscillator (LO) and intermediate frequency (IF) ports and usually are abbreviated as R, L and I. For a single-ended mixer, all the ports are connected to the same diode. Filters typically are used to electrically separate input and output signals to achieve port-to-port isolation as shown in Figure 2.

Assuming that the inputs to the mixer are sinusoids and are applied to the R and L ports and that they can be represented in the form of :

$$A \cos(\omega t) \quad (1)$$

where: A = amplitude of the input signal voltage and current and $\omega = 2\pi f$, where f is the input frequency.

The current-voltage relationship for a diode is:

$$I(V) = I_s \exp(-V_a/V_t) \quad (2)$$

where:

V_a = applied AC and DC voltages
V_t = KT/q
K = Boltzmann's constant
T = Ambient temperature
q = electron charge

Because two sinusoidal input signals (R and L) are being applied simultaneously, the output current of the diode will be in the form of:

$$I(V) = I_s \exp(-(A_1 \cos \omega_r t + A_2 \cos \omega_l t)/V_t) \quad (3)$$

Because of the nonlinear nature of the diode, as evidenced by the exponential form of the current, intermodulation products are created. If the expression in equation (3) is expanded by using a Power series then:

$$I = I_s \sum_{n=1}^{\infty} (A_1 \cos\omega_r t + A_2 \cos\omega_l t)^n / V_t^n! \quad (4)$$

Separating DC and AC terms:

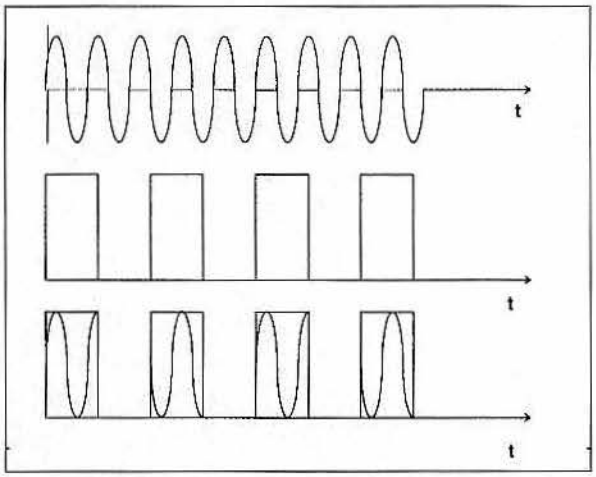


Figure 3. RF and LO ideal waveforms and resultant IF multiplication waveform from LO switching action.

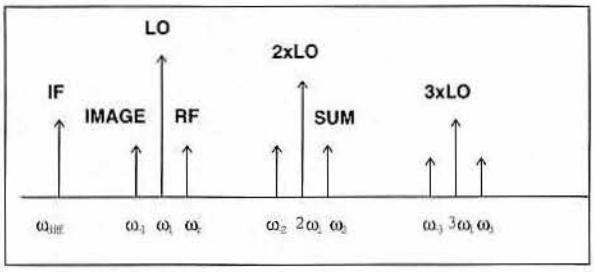


Figure 4. Mixer frequency spectrum (IF and first three spurious groups).

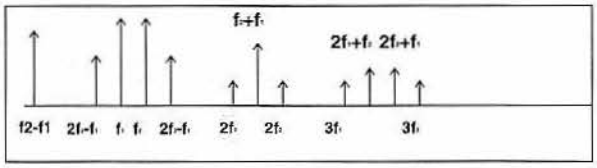


Figure 5. Mixer spectrum caused by two RF input signals and or saturation.

$$i(v) = I_o + I_s \sum_{n=1}^{\infty} (1/V_t^n\, n!)\,((A_1\cos(\omega_r t) + A_2\cos(\omega_l t)) \qquad (5)$$

The magnitude of the higher-order terms of this expression will be controlled by the amplitudes A_1 and A_2 and naturally will decrease due to the n! term in the denominator, assuming small signal operation. If the Fourier transform is taken of Equation 5, the expression of the frequency components will be in the form:

$$\omega_x = m\omega_r + n\omega_l \qquad (6)$$

where x, m and n are positive or negative integers, m and n can take on an infinite amount of integer values, and they represent all the different frequency components that will be contained in the mixer output signal. Obviously, some frequency components will be higher in magnitude than others, because the corresponding voltage and current vary as described in Equation 4.

In addition to the mixing action caused by the nonlinear characteristics of the diode, the diode can be switched on and off to enhance the mixing action. If the LO power >> RF power and the LO power are sufficient to saturate the mixer diode, than the mixer diode switches on and off. The amount of RF power needed to saturate the diode is dependent upon the potential barrier and ideality factor of the device. Because the LO signal amplitude is much greater than the RF signal amplitude, as is the usual case for a mixer, the LO port can be viewed as a switch.

What actually causes the switching action in the diode is a time-varying conductance that is caused by the large LO signal. The instantaneous conductance of the diode g(t) can be found by taking the differential of Equation 3 with respect to voltage (g(t) = di(v)/dv). After taking the differential and performing a series expansion on the quantity, the expression for the diode current can be expressed in the form:

$$\cos((m\omega_l + \omega_r)\,t) + \cos(m\,\omega_{diff} - \omega_r)\,t) \qquad (7)$$

where: ω_{diff} is the frequency difference between RF and LO frequencies (usually the IF freq.) and m = 1,3,5,7 because the square wave is an odd function.

Figure 3 shows the RF input waveform as well as the LO port waveform. Because the diode is switched on and off by the LO signal, the RF signal is sampled at the rate of the LO frequency. The resultant IF waveform is a multiplication of the RF waveform and the LO waveform.

Therefore, the form of the current obtained in Equation 7 can be obtained by noting that the product (mutiplication) of two cosine functions is of this form by trigonometric identity. Because the LO signal is much greater in magnitude than the RF signal, the difference frequency between the LO and RF signals appears as sidebands on either side of the LO signal and its harmonics. This results in an output spectrum as shown in Figure 4.

The LO signal and its harmonics have sidebands spaced at multiples of the difference of the RF and LO frequency, which is the IF frequency. This frequency spectrum is valid only if the RF amplitude is small compared with the LO amplitude. Additional intermodulation products are created when both signals are large.

Referring to Figure 4, Saleh developed a useful nomenclature for numbering the various IF output signals with positive and negative subscripts indicating a difference between frequencies residing above or below the LO signal and its harmonics.

These signals are of most concern:

- ω_l is the local oscillator frequency.
- ω_{diff} is the IF or difference frequency.
- ω_r is the RF signal frequency.
- $\omega_1 = -\omega_l + \omega_{diff.}$, which is also known as the image frequency.
- $\omega_2 = 2\omega_l + \omega_{diff.}$, which is the sum frequency of RF and LO.

Intermodulation products

If two RF signals are applied to the RF port simultaneously, or if the magnitude of the RF signal is not negligible as compared to the LO signal, then additional intermodulation (IM) products are generated by these extra signals. The general form of the IM products follow Equation 6 if the RF signal is not negligible compared with the LO signal. If two tones (two closely-spaced signals) are injected into the mixer, the situation gets worse and results in a frequency spectrum as shown in Figure 5.

This frequency component can be expressed in the form:

$$f_{IM} = +/-\ pf_1 +/- qf_2 +/- nf_{LO}$$

where: p,q and n are integers; f_1 is the first frequency; f_2 is the second frequency.

This is an undesirable spectrum to have in a receiver because it is difficult to filter out all these products. For this reason, most receivers operate in the linear (non-saturated) state, and substantial filtering is used to remove unwanted signals before and after the mixer. The next section describes different types of mixers and the techniques for intermodulation suppression using symmetric diode structures.

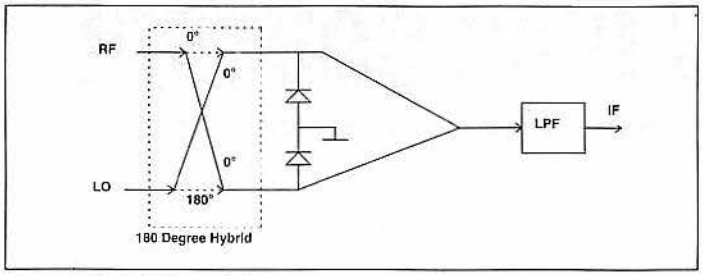


Figure 6. Single-balanced mixer.

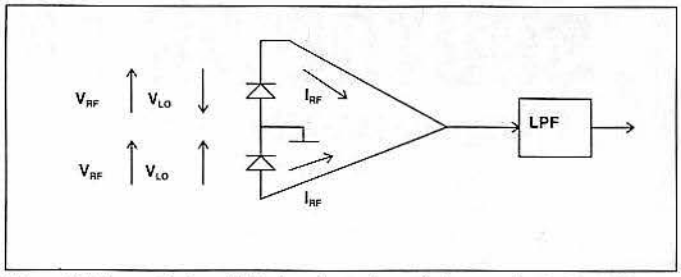


Figure 7. Phase of LO and RF signals at mixer diodes results in IF addition at output.

The single-balanced mixer

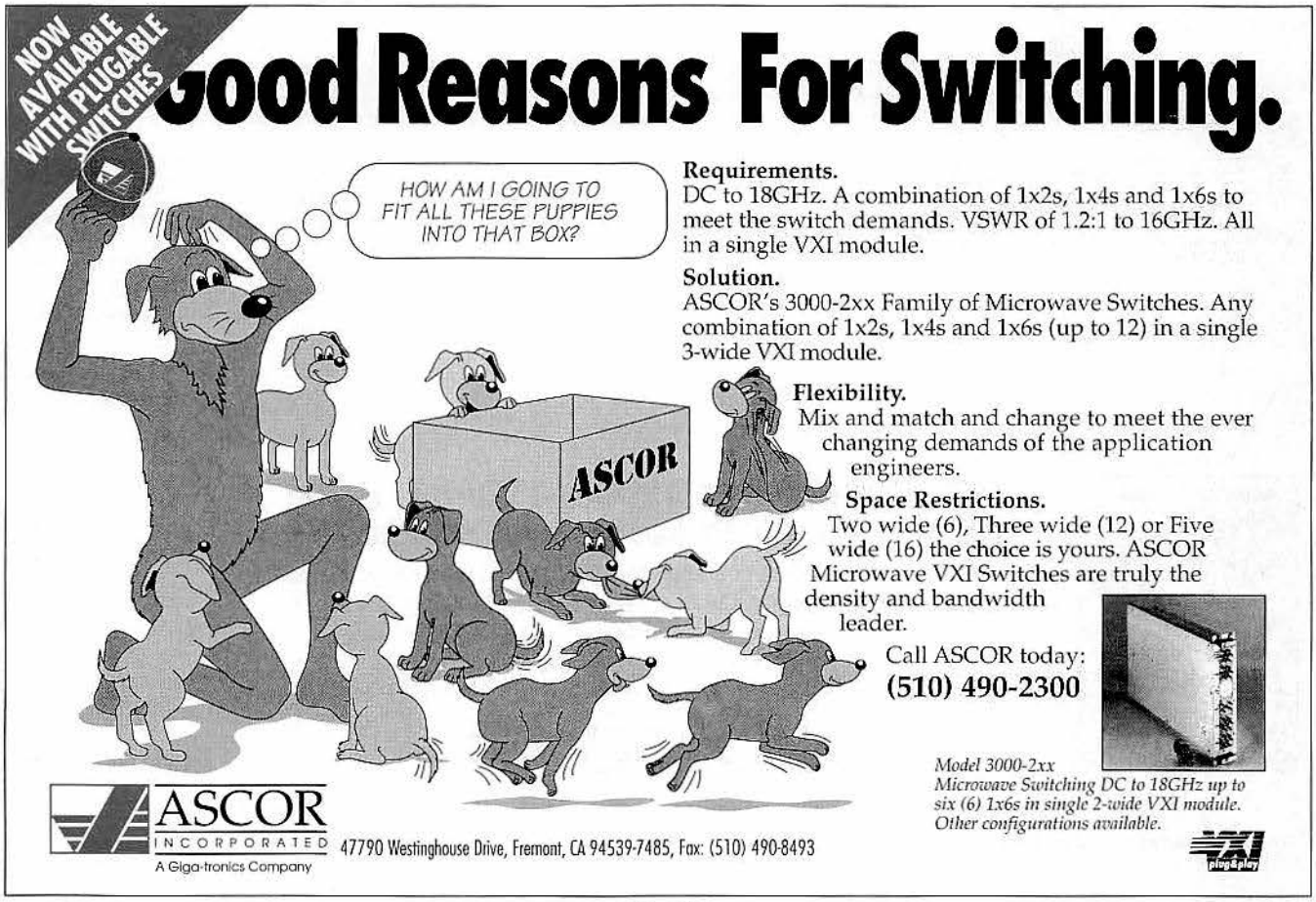
To improve port-to-port isolation and to reduce the magnitude of some of the spurious signals, two diodes commonly are used to create a single-balanced mixer as shown in Figure 6. The single-balanced mixer essentially is two single-ended mixers that are interconnected in a configuration that causes some spurious products to be reduced greatly. This type of mixer typically uses a four-port, 180° hybrid. This takes an input signal and splits it into two equal-amplitude signals that are 180° apart in phase when a signal enters one input port and creates two in-phase signals, if the signal is applied to the other input port.

Figure 6 shows the four ports of a typical 180° hybrid and the corresponding phases. At RF frequencies, the hybrid can be constructed with a ferrite core and small wires. Bifilar is multiconductor transmission line that can split and carry signals in parallel conductors. At microwave frequencies, printed coupled lines can be used to create a hybrid. One of the most popular hybrids is the Lange coupler.

The hybrid is used to achieve phase cancellation in the two diodes to reduce the number of spurious products. Figure 7 shows the phase at various points in the system and how cancellation occurs. The LO signal enters the hybrid at port 1 and creates an in-phase signal at port 2 and a 180° out-of-phase signal at port 3. Because of the phase shift applied to the diodes, the following suppression of signals occur,

1. All (m,n) spurious responses, where m and n are even are eliminated.
2. The (m,n) spurious responses are eliminated if m is even and n is odd, but not if m is odd and n is even.
3. kth order responses where k = m + n arise only for voltage terms of the kth power.

In addition, the 180° hybrid inherently isolates the RF and LO port from each other, which sometimes eliminates the need for RF and LO filtering. Because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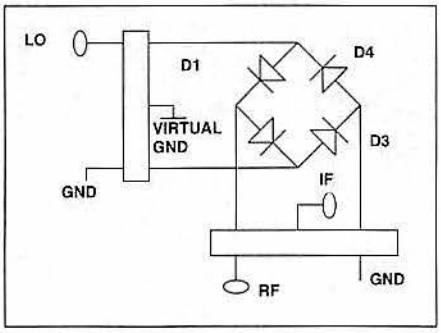

Figure 8. Double-balanced mixer implemented with Baluns.

the signal is split into equal amplitudes in the hybrid, 3 dB of additional power is required compared to a single-ended mixer for the diodes to receive the equivalent LO power. Despite the additional RF power requirement and the added complexity, this type of mixer is popular because it suppresses spurious emissions and it reduces or eliminates the need for RF and LO filters.

The double-balanced mixer

A double-balanced mixer configuration is shown in Figure 8. This configuration consists of four diodes and two balanced mixers connected in a "ring" configuration. Double-balanced mixers use two hybrids instead of one, which improves both the L-R port and R-I port isolation.

A special type of hybrid called a balun commonly is used in this type of mixer. It still provides a phase shift between ports, but also provides a virtual ground for the LO signal from which the IF frequency can be extracted. Because of its highly balanced and symmetrical configuration, this type of mixer theoretically supresses 75% of the possible IM products. The only products that have appreciable content are those with either odd LO or odd RF harmonics (harmonics with n or m = 1,3,5,7....).

In the double-balanced mixer, two diodes are on and the other two are off because of the way the signals are applied to the diodes. Referring to Figure 8, D1 and D2 are on, and D3 and D4 are off. This causes the switching action that was described before that

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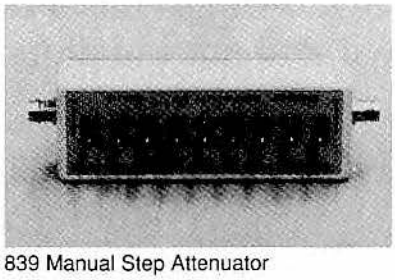

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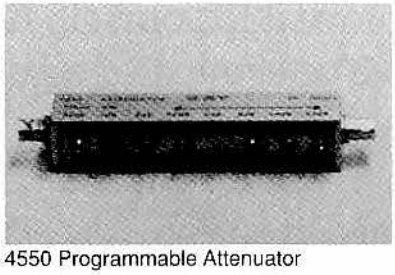

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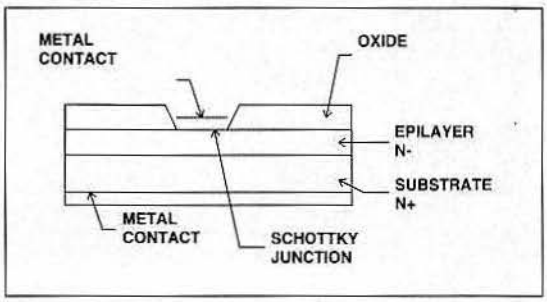

Figure 9. The Schottky diode structure.

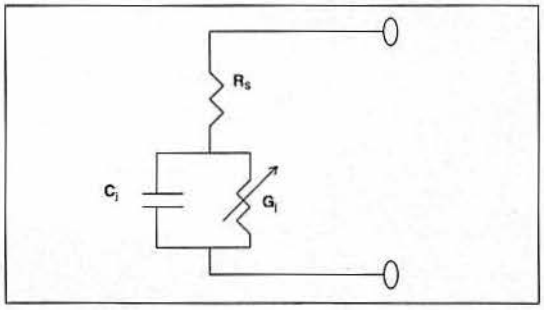

Figure 10. Equivalent circuit of a Schottky diode.

causes mixing. Of course, because two hybrids are involved, an additional 3 dB of both LO and RF power is required to drive this type of mixer as compared to a single balanced mixer.

In addition, the diode characteristics should match each other closely or spurious suppression will decrease. To achieve good results, the diodes usually are fabricated together on one piece of semiconductor and interconnected at the chip level.

Semiconductor devices

As described before, the nonlinearity and switching in the mixer device are the two most important factors for mixing. Not all types of semiconductor devices are suitable for this type of component. The most commonly used devices for mixers include Schottky diodes, FETs and small-signal bipolar devices.

• *The Schottky diode* — The Schottky diode is a specially fabricated device that is formed from a metal-semiconductor interface. Because the diode is not made from a p - n junction, it is a majority carrier device. Figure 9 shows a typical configuration of the device. The semiconductor consists of a heavily-doped substrate with a thin, lightly-doped layer deposited on top of it and a layer of metal deposited on top of the thin layer.

This configuration allows the diode to have low capacitance caused by the metal semiconductor interface as well as low resistance, caused by the highly-doped n+ layer. Because the mixer switches at the LO frequency and relies on the fast-switching action for mixing, it is imperative that the diode has low junction resistance and capacitance because its switching time is related directly to the RC time constant of the junction. The expression for the diode

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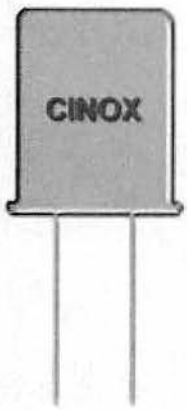

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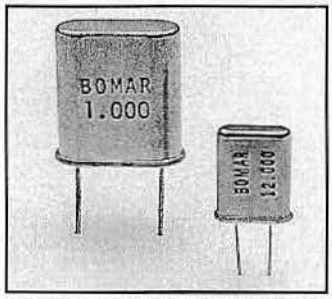

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capacitance is:

$C(V) = C_{jo}/(1 - V/\phi_{bi})$

where: C_{jo} is the zero bias capacitance; ϕ(bi) the built-in potential of the metal semiconductor junction

The small-signal diode model is shown in Figure 10. It consists of a junction capacitance in parallel with a junction conductance and a series resistance. The typical capacitance for a Shottky diode for mixer diodes is typically 1 pf or less, and the typical series resistance is 10 Ω or less.

Because the capacitance and resistance are quite low, the diode switches at a fast rate, which facilitates the mixing action. A figure of merit that often is used is the cutoff frequency, which is:

$f_c = 1/2\pi R_s C_{jo}$

The rule of thumb for mixer operation is for the LO frequency to be 1/40th of the cutoff frequency to ensure a quick switching time. As a result, the RC time constant of the diode would be low compared to the LO frequency time constant of one RF cycle.

Key mixer parameters

Conversion loss—Figure 11 shows a single diode mixer with matching circuits at the RF and IF ports. An ideal match theoretically can be achieved at one frequency. Nevertheless, in practice there is always a finite mismatch that results in RF loss. This RF loss is known as the conversion loss, which is defined as:

Conversion loss = available RF signal input power/available IF output power

There are two components to conversion loss, one caused by circuit mismatch and another caused by intrinsic loss in the diode because finite junction capacitance and resistance (along with the series resistance) exsist.

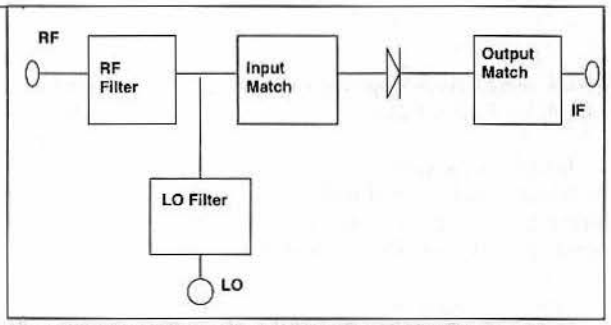

Figure 11. Single-diode mixer with input and output matching.

The approximate conversion loss caused by the diode itself is:

$L_{diode} = 1 + R_s/R_j + \omega^2 C_j^2 R_s R_j$

where R_s and R_j and C_j are the series and junction resistance and capacitance, respectively.

Assuming a matched condition at the RF and IF ports, the total mixer conversion loss in dB is approximated by:

$L_{total} = 10 \log (Z_o(g_o + g_2 + 1/Z_o))((g_o(g_o + g_2 + 1/Z_o)/g_1^2)-2)$

where: Z_o is the RF, LO and IF port impedance; g_0, g_1 and g_2 are the first

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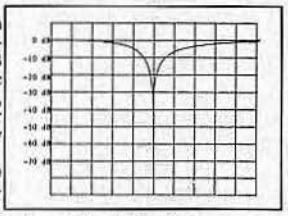

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three terms from a series expansion of the diode conductance.

If the image and sum frequencies are reflected back into the diode by using open and short circuits at those frequencies, then conversion loss can be improved because this reflected power can be converted into IF power. Typical conversion losses of a single diode mixer are usually in the range of 3–4 dB.

•*Noise figure* — The other key parameter of a mixer is noise figure. The noise figure of a cascade of circuits is defined as:

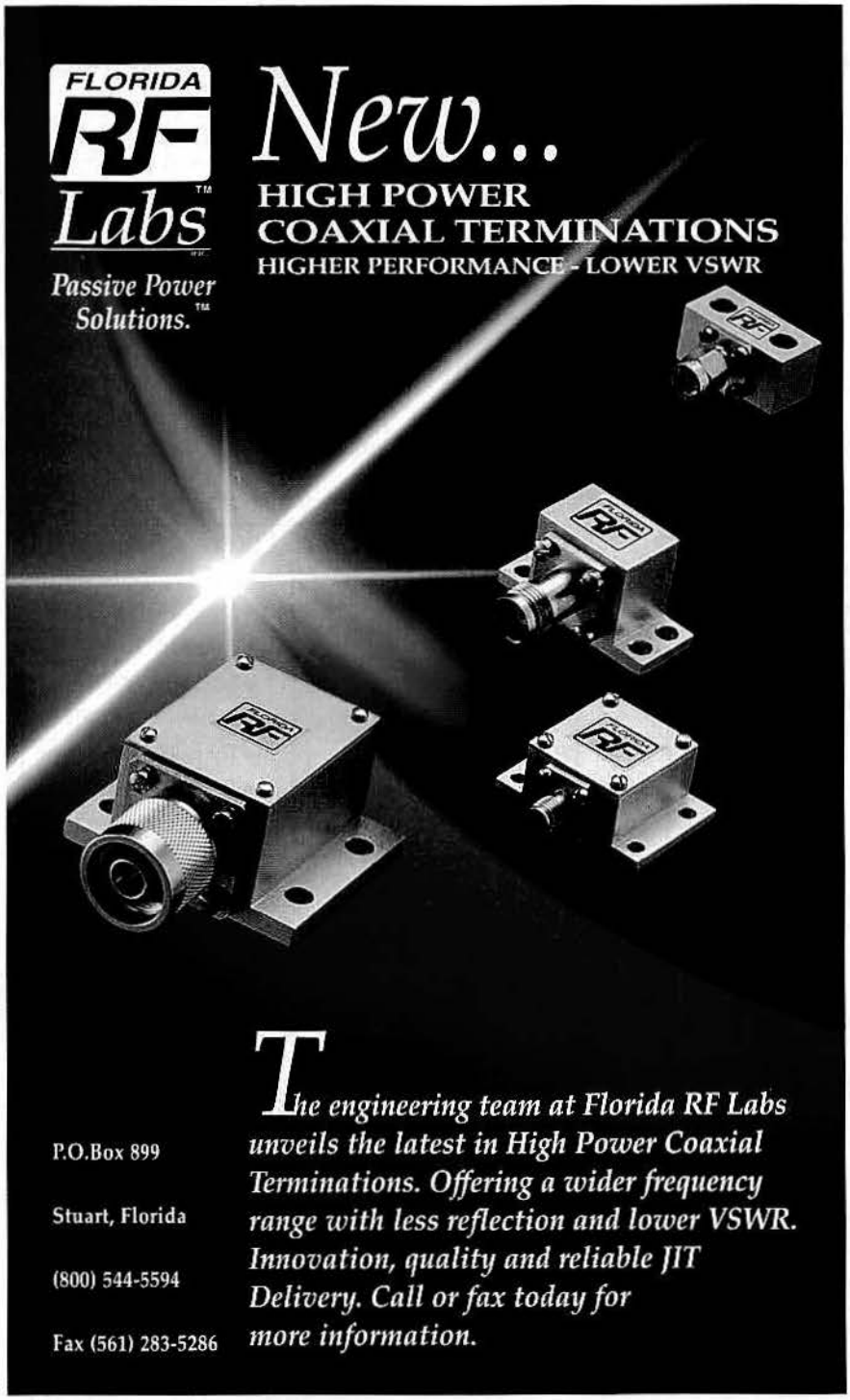
$$F = F_1 + F_2 - 1/G_1 + F_3 - 1/G_1G_2$$

This equation indicates that the first-stage noise figure controls the noise figure of a system. A typical downconverter cascade that included a mixer was shown in Figure 1. Oftentimes, in receivers, the first stage is a mixer. In practice, the noise figure always is measured in reference to a characterized noise source. Noise in mixers is caused by the resistive components as well as noise sources related to electron flow in the diode. Typical noise figures for a diode mixer are in the 3–4 dB range.

•*Port-to-port isolation* — Port-to-port isolation is defined as the amount of RF power that leaks from one port of a mixer to another. These include RF-to-IF, RF-to-LO, LO-to-IF, LO-to-RF, IF-to-LO and IF-to-RF isolation. This isolation nomenclature defines the first port as the source of the RF signal and the second port as the port where the leakage is measured. As described earlier, single-diode mixers have the worst isolation, and double-balanced mixers have much better isolation. This is caused by the natural isolation of a hybrid or balun in balanced configurations. This parameter also can be improved by using filters at the various ports to improve the frequency selectivity of the mixer. Typical isolation values range from 10 to 25dB depending on the type of mixer.

Conclusion

An introduction to mixers has included the role of mixers, theory of operation, types of mixers, semiconductor devices and key figures of merit. *RF*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Roland Soohoo received a B.S.E.E. from the University of California at Davis and an M.S.E.E. from the University of Santa Clara. He worked for Avantec in R & D and program management functions from 1985 - 1991. He was a project leader for Hewlett-Packard from 1991-1996 leading a cross functional team for development of RF and MMW subsystems and components. He joined Fujitsu Microelectronics in late 1996, where he is product marketing manager in the wireless products group in San Jose, CA.